JÜLICH
FORSCHUNGSZENTRUM

Interactive visualization and steering of structural plasticity in NEST

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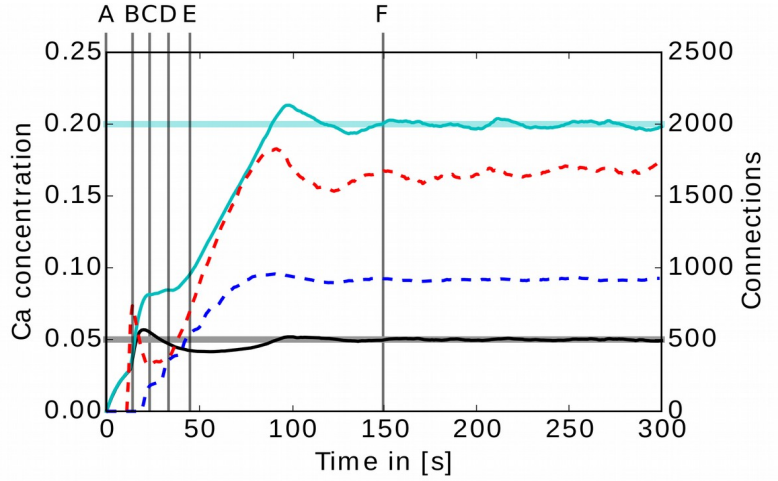
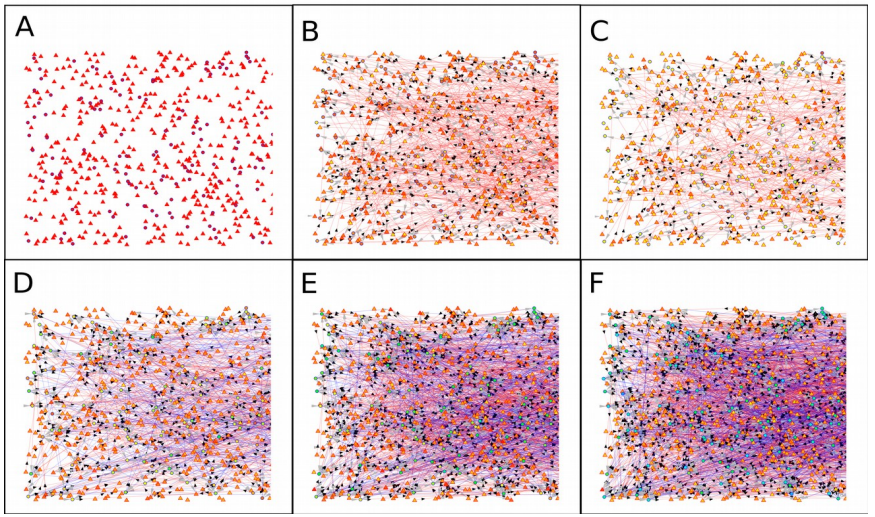
Agenda

- Introduction: what is structural plasticity?
- Which model are we using and how is it implemented in NEST?
- Interactive visualization and steering tool
- Use case
- Results
- Conclusions

What is structural plasticity?

- Structural plasticity refers to the ability of a neural network to physically create and remove connections.
- Plays a role in the modeling of learning, memory [1], recovery after lesions [2] and brain development [3].

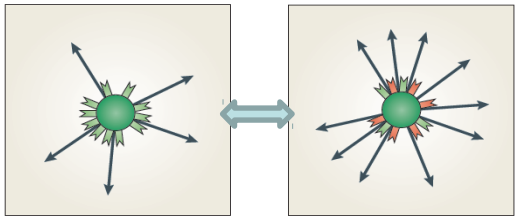




Which model are we using?

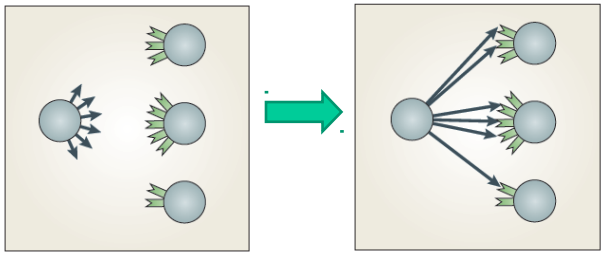
- The model we implemented in NEST is described in Butz & van Ooyen 2013 [4]:
  –

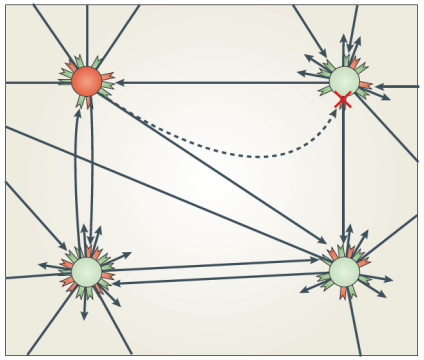
Synaptic elements



Axonal bouton: presynaptic element
Dendritic spine: exc. postsynaptic element
Dendritic spine: inh. postsynaptic element

Synapse formation/deletion





Which model are we using?

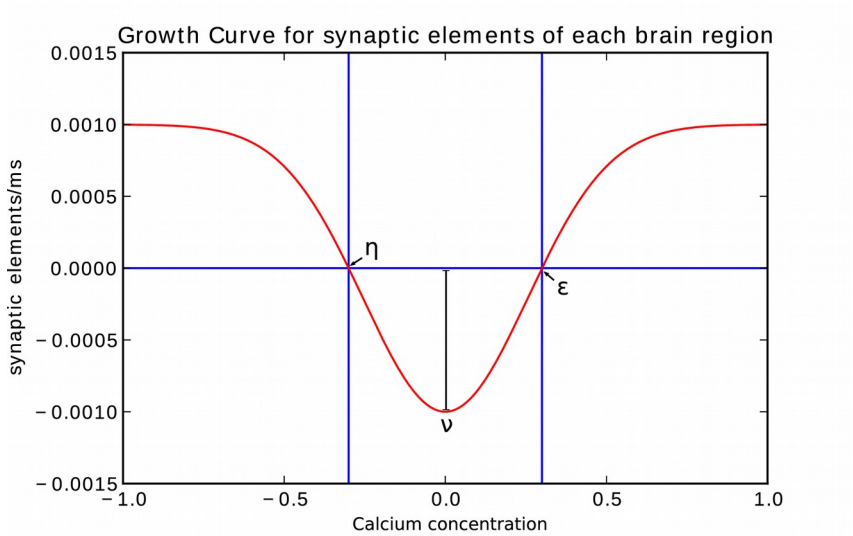
- The algorithm consists of 3 repeating parts:
  - (1) Update calcium concentration in neurons based on electrical activity.

$$\frac{d\mathrm{Ca}}{dt} = \begin{cases} -\frac{Ca(t)}{\tau} + \beta & \text{if the neuron fires} \\ -\frac{Ca(t)}{\tau} & \text{otherwise} \end{cases}$$

Where is the calcium intake coefficient and is the calcium decay coefficient.

Which model are we using?

- (2) Update the number of synaptic elements
  - Growth rules: linear and Gaussian

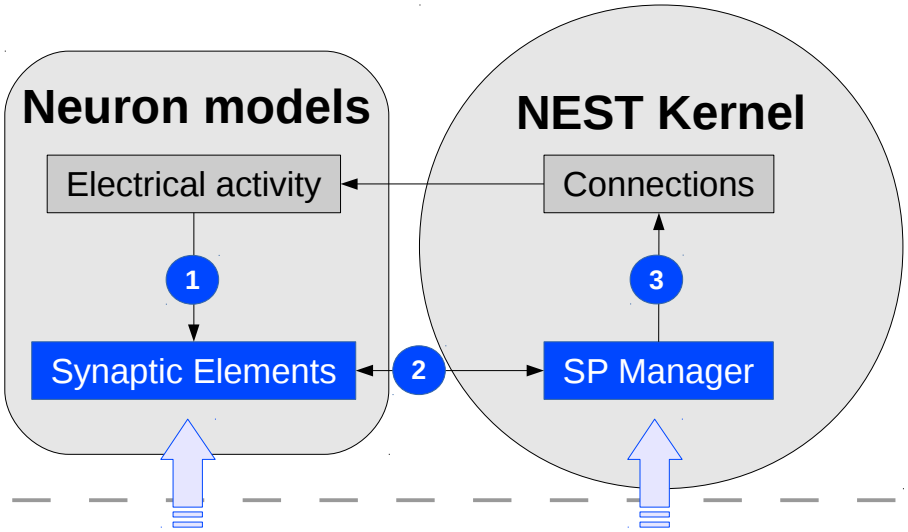


η is the minimum level of Ca2+ to start generating or deleting elements (depending on the sign of ν)
ν is the growth rate
ε is the target calcium concentration

Which model are we using?

- (3) Update the network connectivity
  - If new synaptic elements are available, new synapses can be formed.
  - If a synaptic element is deleted, the synapse will be broken but the counterpart will remain and can be used to create a new synapse.

Implementation in NEST



1. The number of **synaptic elements** is updated depending on the electrical activity of the neurons

The **SP manager**:

2. Gathers the number of synaptic elements per neuron
3. Creates/deletes synapses to update the connections between the neurons

Navigating the parameter space

- Simple, well defined setups, usually reach stability.
- A big challenge arises when structural plasticity is enabled simultaneously on several highly interconnected populations with possibly differing levels of activity.
- The speed at which the synaptic elements are created has a large impact on reaching an stable configuration.
- The delay in updating the connectivity of the network strongly influences the performance and stability of the system as well.

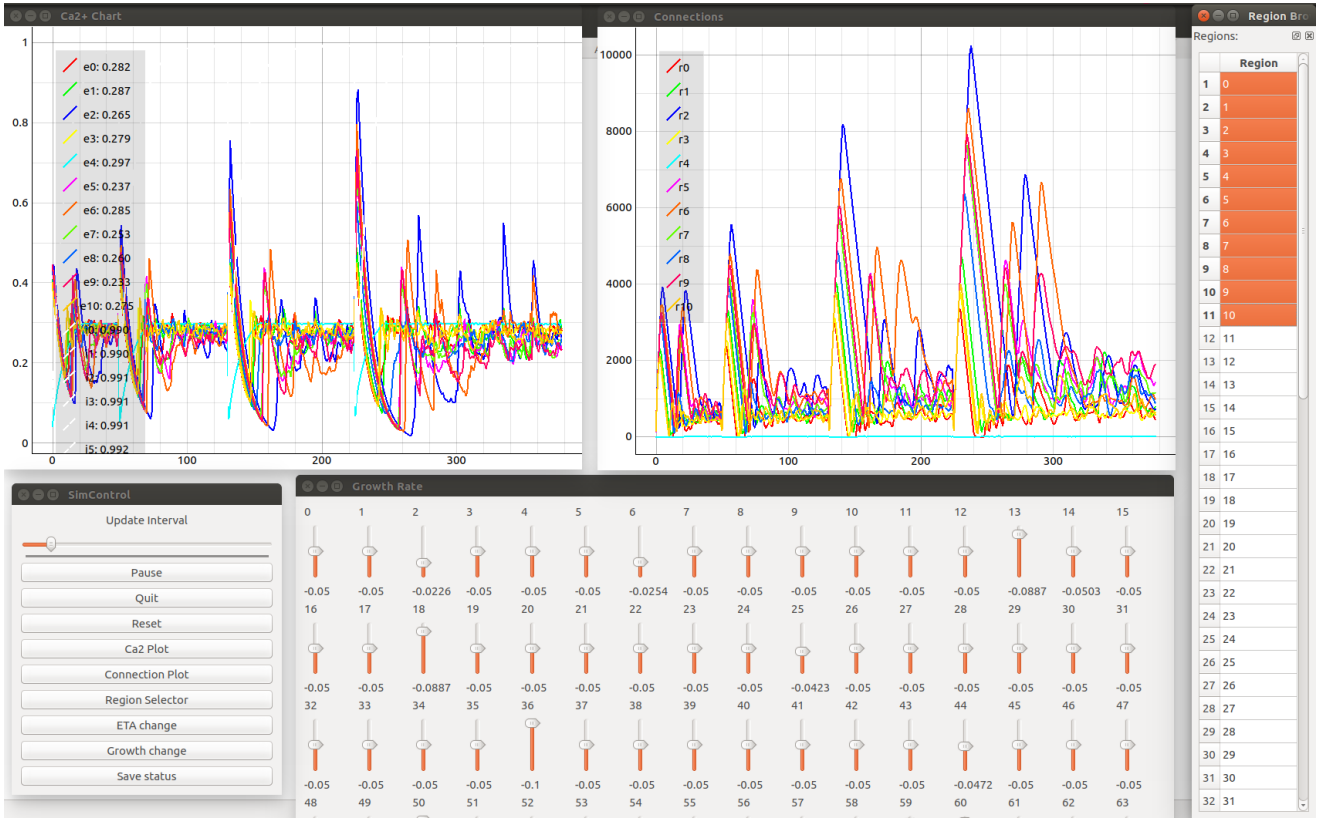
Navigating the parameter space

The dynamic nature of working with structural plasticity requires:

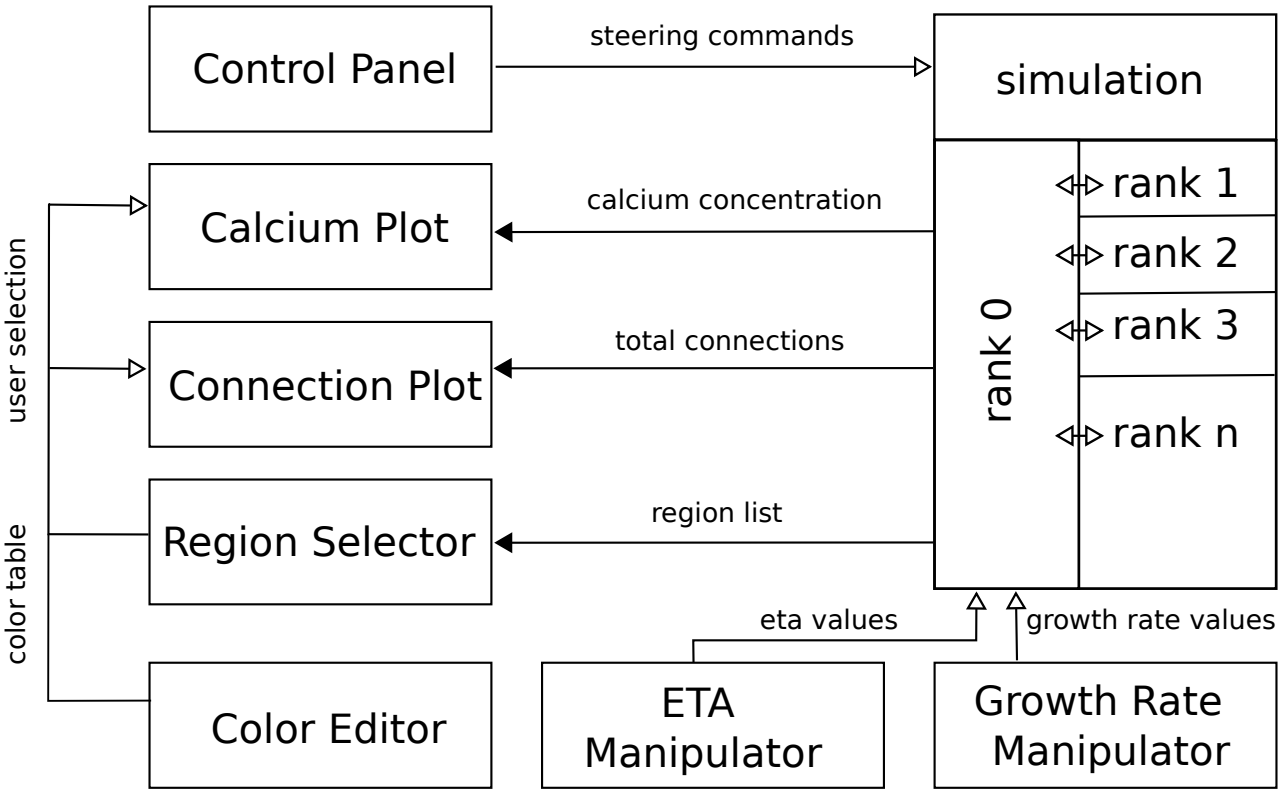
- The simultaneous analysis of several changing variables.
- The ability to compare the level of activity of several regions simultaneously.
- The ability to change simulation parameters at any moment in each region of the network.
- The ability to snapshot a time point in the simulation and store the connectivity state.
- The ability to load a previously stored state.

Navigating the parameter space

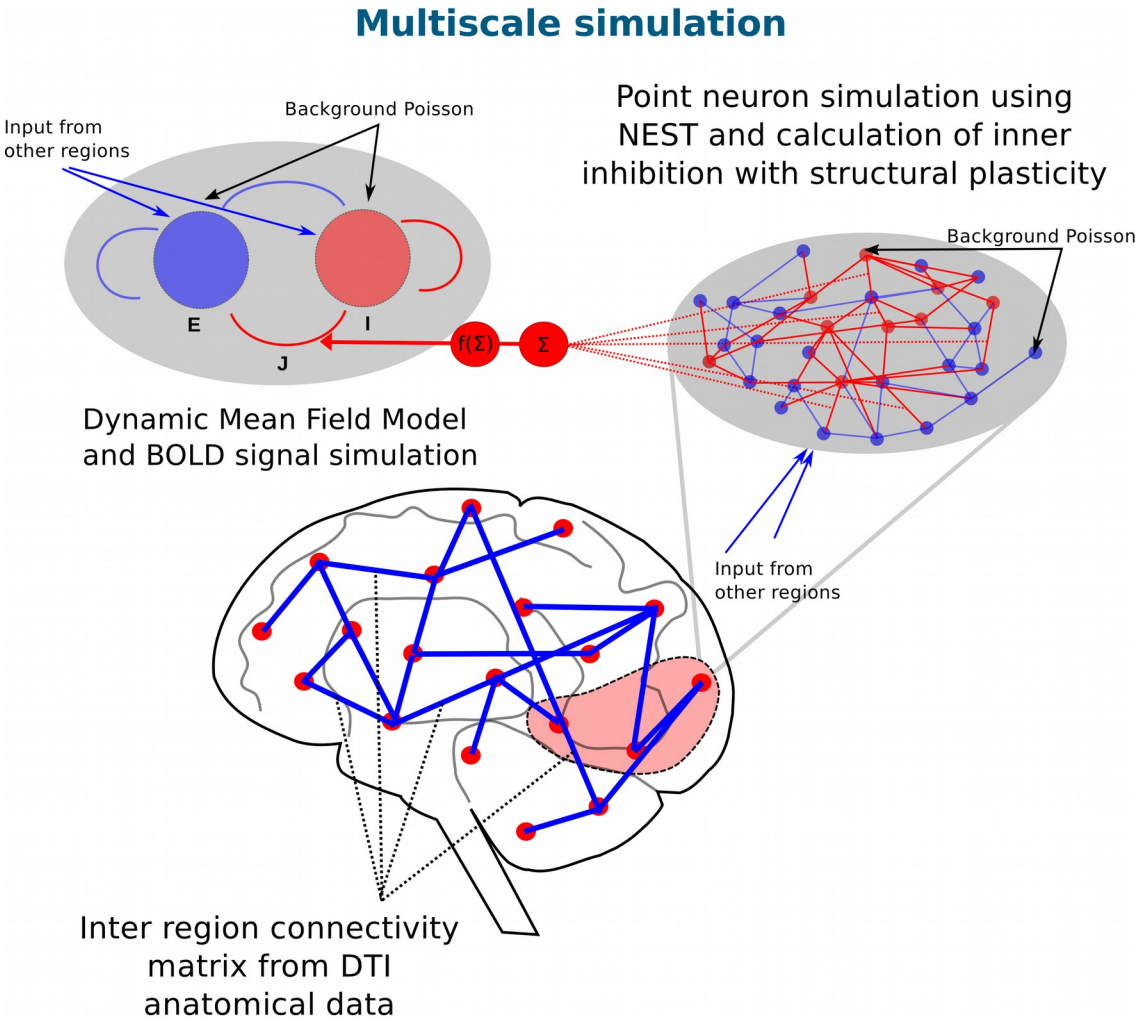
- Our solution was to develop an interactive visualization tool which was designed to address all the needs listed previously.



Navigating the parameter space



Use case: Multiscale Neural Mass Simulation



Results

- Video

Conclusions

- The implementation of structural plasticity in NEST can be used to generate the connectivity for a large network from scratch or to fill in missing connectivity information.
- Our interactive steering tool allows users to navigate through the dynamic parameter space of structural plasticity and reach stable setups for complex multi-population and highly interconnected networks.
- This tool will be available to NEST users soon. The tool can be configured to different setups easily and used on supercomputers.

References

(1) Lamprecht, Raphael, and Joseph LeDoux. "Structural plasticity and memory." Nature Reviews Neuroscience 5.1 (2004): 45-54.

(2) De Paola, V., Holtmaat, A., Knott, G., Song, S., Wilbrecht, L., Caroni, P., & Svoboda, K. (2006). Cell type-specic structural plasticity of axonal branches and boutons in the adult neocortex. Neuron 49 (6), 861875.

(3) Hensch, T. K. (2005). Critical period plasticity in local cortical circuits. Nat. Rev. Neurosci. 6 (11), 877888.

(4) Butz, M., & van Ooyen, A. (2013). A simple rule for dendritic spine and axonal bouton formation can account for cortical reorganization after focal retinal lesions. PLoS Comput. Biol. 9 (10), e1003259.

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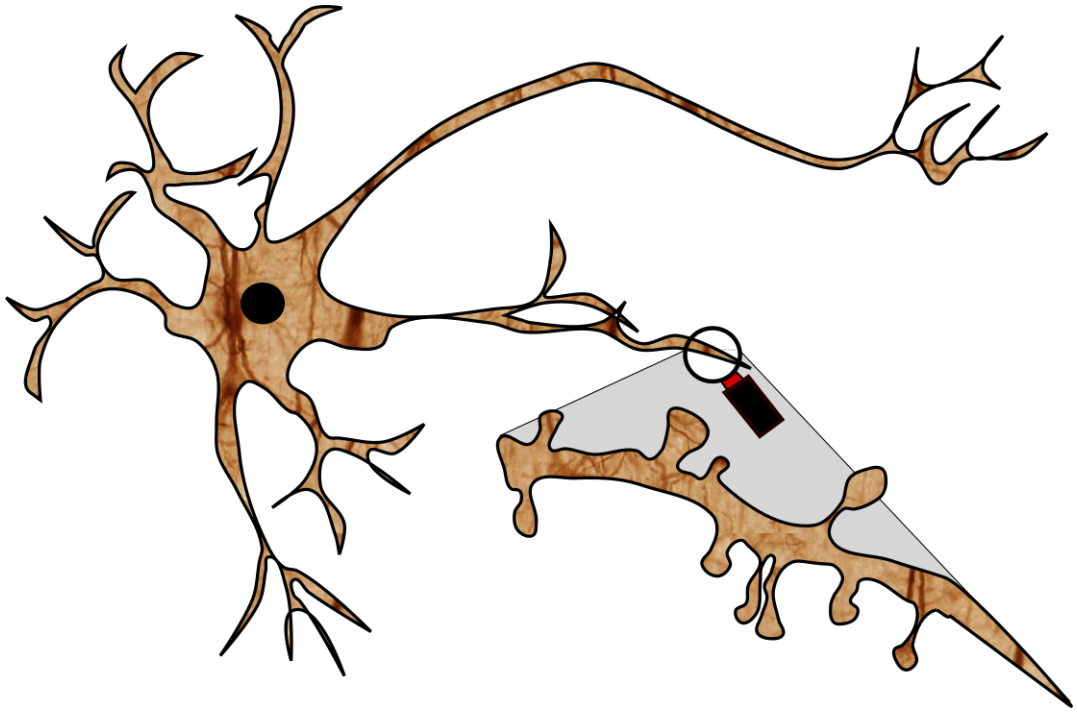
(6) G. Deco, A. Ponce-Alvarez, P. Hagmann, G. L. Romani, D. Mantini, and M. Coretta. How local excitation inhibition ratio impacts the whole brain dynamics. The Journal of Neuroscience, 34(23):7886 7898, 2014.

Thanks for your attention

Questions?



Use case

- In the configuration used here, only inhibitory connections can be created.
- The desired electrical activity has a frequency of 3 Hz and an inverted Gaussian curve describes the growth rate of connection points for neurons.
- It is important to note that in this work, we are only focusing on the calculation of connectivity for the large scale simulation.
- The comparison of the results obtained by the simulation of the whole brain using the DMFM model and is subject of future work.

Use case

- The use case was born from the need to better understand the relationship between connectivity and function in the brain at different scales.
- We use point-neuron network simulations in NEST to complement connectivity information for whole brain simulations based on a Dynamic Mean Field Model (DMFM) based on a spiking network model in Wong & Wang 2006 [5] and the setup by Deco et al. 2014 [6].
- Structural plasticity is used to calculate the inner inhibitory connectivity required to match experimentally observed firing rates inside each region.
- The resulting connectivity is then input to the DMFM.
- The output of subsequent simulations of the DMFM (a simulated BOLD signal) can be compared with experimental fMRI data in order to findcorrelations between function and structure.

Use case

- Structural data obtained by Diffusion Tensor Imaging is used to initialize our simulation using NEST. These synapses are fixed and can not be deleted by the structural plasticity algorithm.
- The simulation is based on 68 regions of 200 integrate-and-fire neurons per region. Each region has two populations, one excitatory (80%) and one inhibitory (20%)